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Azimuthal Asymmetric Distribution of Hadrons Inside a Jet at Hadron Collider

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Abstract

We study the azimuthal asymmetric distribution of hadrons inside a high energy jet in the single transverse polarized proton proton scattering, coming from the Collins effect multiplied by the quark transversity distribution. We argue that the Collins function in this process is the same as that in the semi-inclusive deep inelastic scattering. The experimental study of this process will provide us important information on the quark transversity distribution and test the universality of the fragmentation functions.

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1. Introduction. Quark transversity distribution is one of the most important quark distributions of nucleon which remains unknown [1, 2, 3]. It is a quark distribution when the nucleon is transversely polarized. Unlike the polarized quark distribution in a longitudinal polarized nucleon, the quark transversity is difficult to measure because it is a chiral-odd distribution [2]. For example, it can not be studied in the inclusive deep inelastic scattering (DIS), which can only probe the chiral-even parton distributions. The Drell-Yan lepton pair production in pp scattering can be used to study the quark transversity distributions [1, 2], but have limited access to them at the collider experiment at RHIC [4].

There have been suggestions to probe the quark transversity from other processes [3]. For example, in Ref. [5], it was proposed to study the quark transversity distributions from the semi-inclusive hadron production in the DIS (SIDIS) process, which can couple with another chiral-odd fragmentation function, the so-called Collins fragmentation function, to lead to a nonzero azimuthal single spin asymmetry (SSA). This SSA has been studied by the HERMES collaboration at DESY [6], and a very interesting result on the Collins fragmentation function was found [7]. The Collins effect in the back-to-back two-hadron production in e^+e^- annihilation has also been explored by the BELLE collaboration [8], and a first attempt to extract the quark transversity distribution from the combined analysis of these two experiments has been reported recently [9]. The interference fragmentation function for two-hadron production has also been suggested to study quark transversity distribution in DIS and hadronic reactions [10].

In this paper, we investigate the possibility to explore the quark transversity distribution in pp collision at RHIC, by studying the azimuthal asymmetric distribution of hadrons inside a jet [11]. We are interested in the hadron production from the fragmentation of a transversely polarized quark which inherit transverse spin from the incident nucleon through transverse spin transfer in the hard partonic scattering processes [11, 12]. As we show in Fig. 1, we will study the process,

$$p(P_A, S_\perp) + p(P_B) \to jet(P_J) + X \to H(P_h) + X \ , \tag{1}$$

where a transversely polarized proton with momentum P_A scatters on another proton with momentum P_B, and produces a jet with momentum P_J (transverse momentum $P_\perp$ and rapidity y_1 in the Lab frame). The three momenta of P_A, P_B and P_J will form the so-called reaction plane. Inside the produced jet, the hadrons are distributed around the jet

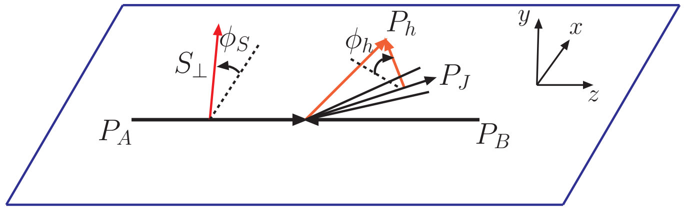

FIG. 1: *Illustration of the kinematics for the azimuthal distribution of hadrons inside a jet in pp scattering.*

axes, and we are interested in studying the azimuthal distribution of a particular hadron H. This hadron will carry certain longitudinal momentum fraction of the jet, and its transverse momentum P_{hT} relative to the jet axis will define an azimuthal angle with the reaction plane: ϕ_h, as shown in Fig. 1. Similarly, we can define the azimuthal angle of the transverse polarization vector of the incident polarized proton: ϕ_s.

The leading order contribution to the jet production in pp collision comes from $2 \to 2$ sub-processes, where two jets are produced back-to-back in the transverse plane. For the reaction process of (1), one of the two jets shall fragment into the final observed hadron. In this paper, we study the physics in the kinematic region of $P_{hT} \ll P_\perp$. We assume a factorization for this process, where we can separate the jet production from the hadron fragmentation [13]. From our calculations, we find that there exists a correlation between the above two azimuthal angles ϕ_h and ϕ_s, coming from the quark transversity multiplied with the Collins fragmentation function. The study of this azimuthal asymmetry will provide us important information on the quark transversity distributions, and will also provide a crucial test for the universality of the Collins fragmentation function by comparing with the Collins effects in other processes. We note that the Sivers effect [14] does not contribute to the correlation between ϕ_h and ϕ_s, because it is azimuthal symmetric as function of ϕ_h.

2. Azimuthal asymmetric distribution of hadron inside a jet. The Collins function describes a transversely polarized quark jet fragmenting into an unpolarized hadron, whose transverse momentum relative to the jet axis correlates with the transverse polarization vector of the fragmenting quark. In the fragmentation process, the observed hadron carries certain momentum fraction (z_h) of the jet, and its momentum can be written as $P_h = z_h P_J + P_{hT}$, where P_{hT} is a transverse momentum relative to the jet momentum P_J, i.e., $P_{hT} \cdot P_J = 0$. We notice that P_{hT} may not be a transverse momentum in the Lab

frame as shown in Fig. 1. In order to observe the Collins effect in the final state hadron distribution, the fragmenting quark has to be transversely polarized. This can be achieved in pp collision by scattering a transversely polarized quark in the partonic process $qb \to qb$, where the final state quark q can inherit the transverse polarization from the initial state quark q, and b represents any other parton from the unpolarized proton. Thus, this Collins effect will depend on the quark transversity distribution of the transversely polarized proton in the initial state. The contribution to the transverse-spin dependent cross section for the process (1) from the $2 \to 2$ subprocess $qb \to qb$ can be calculated, and we find that

$$\frac{d\sigma(S_\perp)}{d\mathcal{P}.\mathcal{S}.} = \sum_{b=q,g} x' f_b(x') x \delta q_T(x) \delta\hat{q}(z_h, P_{hT}) \frac{\epsilon^{\alpha\beta} S_\perp^\alpha}{M_h} \times \left[P_{hT}^\beta - \frac{P_B \cdot P_{hT}}{P_B \cdot P_J} P_J^\beta \right] \times H_{qb\to qb}^{\rm Collins} \ , \tag{2}$$

where $d\mathcal{P}.\mathcal{S}. = dy_1 dy_2 dP_\perp^2 dz d^2 P_{hT}$ represents the phase space for this process, y_1 and y_2 are rapidities for the jet P_J and the balancing jet, respectively. $P_\perp$ is the jet's transverse momentum. The final observed hadron's kinematic variables z_h and P_{hT} are defined above. Here, x and x' are the momentum fractions carried by the quark "q" and parton "b" from the incident polarized and unpolarized nucleons. f_b is the parton distribution for "b", $\delta q_T(x)$ (also noted as δq, h_{1q} and $\Delta_T q$ in the literature) is the quark transversity distribution, and $\delta\hat{q}$ the Collins fragmentation function [5] (also noted as $\Delta\hat{D}$ or $H_1^\perp$ in the literature). The quark transversity and the Collins function follow the convention used in [7, 15], which is different from the so-called Trento convention for the Collins function: $\hat{\delta} q \equiv -H_1^\perp/z_h$. $H_{qb\to qb}^{\rm Collins}$ is the hard factor for the partonic channel $qb \to qb$. Because the quark chirality is conserved, we only have the following channels contributing to the above cross section: $qq'(\bar{q}') \to qq'(\bar{q}')$, $qq \to qq$ and $qg \to qg$, and those with the anti-quark transversity. The hard factors are

$$\begin{aligned} H_{qq'\to qq'}^{\rm Collins} &= H_{q\bar{q}'\to q\bar{q}'}^{\rm Collins} = \frac{\alpha_s^2 \pi}{\hat{s}^2} \frac{N_c^2-1}{4N_c^2} \frac{4\hat{s}\hat{u}}{-\hat{t}^2} \ , \\ H_{qq\to qq}^{\rm Collins} &= \frac{\alpha_s^2 \pi}{\hat{s}^2} \frac{N_c^2-1}{4N_c^2} \left[\frac{4\hat{s}\hat{u}}{-\hat{t}^2} - \frac{1}{N_c} \frac{4\hat{s}}{-\hat{t}} \right] \ , \\ H_{qg\to qg}^{\rm Collins} &= \frac{\alpha_s^2 \pi}{\hat{s}^2} \left[\frac{N_c^2-1}{N_c^2} + \frac{1}{2} \frac{4\hat{s}\hat{u}}{-\hat{t}^2} \right] \ , \end{aligned} \tag{3}$$

where $\hat{s}$, $\hat{t}$, and $\hat{u}$ are the usual partonic Mandelstam variables. The hard factors for the partonic channels associated with the antiquark transversity are the same as the above. Not surprisingly, these hard factors are exactly the same as those calculated for the transverse spin transfer in the hard partonic processes [11, 12].

With the kinematics shown in Fig. 1, the above differential cross section can be further simplified, because $\epsilon^{\alpha\beta}S_\perp^\alpha\left[P_{hT}^\beta-\frac{P_B\cdot P_{hT}}{P_B\cdot P_J}P_J^\beta\right]=|S_\perp||P_{hT}|\sin(\phi_h-\phi_S)$, where ϕ_S and ϕ_h are the azimuthal angles defined above. The differential cross sections for the hadron distribution in a jet can then be summarized as

$$\frac{d\sigma}{d\mathcal{P}.\mathcal{S}.}=\frac{d\sigma_{UU}}{d\mathcal{P}.\mathcal{S}.}+|S_\perp|\frac{|P_{hT}|}{M_h}\sin(\phi_h-\phi_s)\frac{d\sigma_{TU}}{d\mathcal{P}.\mathcal{S}.}\ , \tag{4}$$

where $d\sigma_{UU}$ and $d\sigma_{TU}$ are the the spin-averaged and single-transverse-spin dependent cross section terms, respectively. They are defined as

$$\begin{aligned}\frac{d\sigma_{UU}}{d\mathcal{P}.\mathcal{S}.}&=\sum_{a,b,c}x'f_b(x')xf_a(x)D_c^h(z,P_{hT})H^{uu}_{ab\to cd}\ ,\\ \frac{d\sigma_{TU}}{d\mathcal{P}.\mathcal{S}.}&=\sum_{b,q}x'f_b(x')x\delta q_T(x)\delta\hat{q}(z,P_{hT})H^{\rm Collins}_{qb\to qb}\ ,\end{aligned}\tag{5}$$

where the hard factors for the spin-averaged cross sections are identical to the differential partonic cross sections: $H^{uu}_{ab\to cd}=d\hat{\sigma}^{uu}_{ab\to cd}/d\hat{t}$.

3. Universality of the Collins fragmentation function. The Collins asymmetry has been studied by the HERMES collaboration in the SIDIS process [6], and by the BELLE collaboration in e^+e^- annihilation [8]. In order to use their constraints to predict the asymmetry of Eq. (4) in the pp collisions, we will assume the universality of the Collins functions in these processes. In Ref. [16], it has been shown that the Collins function is universal between the DIS and e^+e^- annihilation processes, which was later argued on a more general ground from the factorization property of the relevant processes [17].

In the following, we will extend the universality discussion to our case, and argue that the Collins function of the hadron production in a jet fragmentation in pp collision will be the same as that in the SIDIS process. The way we demonstrate the universality is similar to the model calculation in [16]. The conclusion, however, does not depend on the model. As we show in Fig. 2, we use a generic model to couple the find state hadron to the fragmenting quark [5], which is produced, for example, from the partonic process $q(S_\perp)q'\to q(s_\perp)q'$, with both the initial and final state quarks transversely polarized. We focus on the discussions for this particular channel, and all other channels follow accordingly [18].

For the single-transverse-spin dependent cross section from the Collins effect, we need to generate a phase from the scattering amplitudes to have a non-vanishing SSA. If the phase comes from the vertex associated with the fragmenting quark and the final state

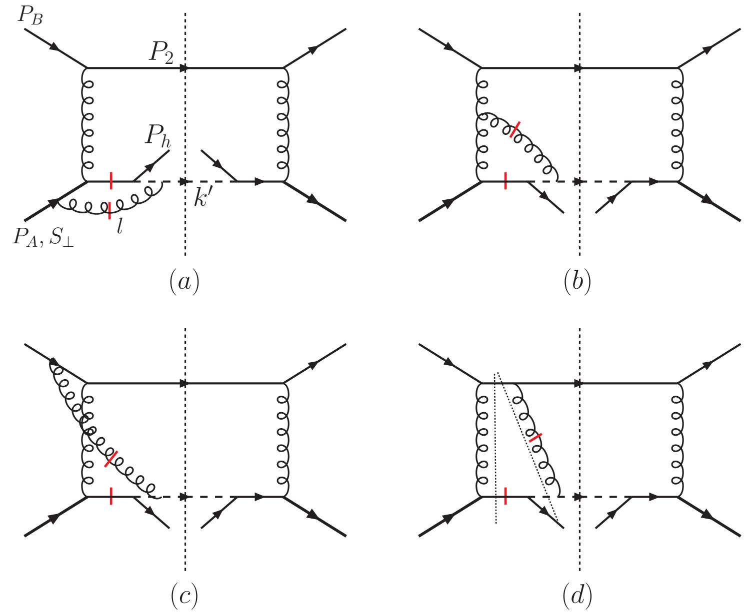

FIG. 2: *Gluon exchange diagrams contributions to the Collins asymmetry in pp collisions. The short bars indicate the pole contributions to the phase needed for a non-vanishing SSA. The additional two cuts in (d) cancel out each other.*

hadron [5], or from the dressed quark propagator [19], it is easy to argue the universality of the Collins function between our process and the SIDIS/e^+e^- process, because they are the same. The main issue of the universality discussion concerns the extra gluon exchange contribution between the spectator and hard partonic part [16]. For example, in our case, because the hadron is colorless while the quark is colored, the remanet in the fragmentation process will be also colored. Thus the gluon exchanges between the remanet and the other parts of the scattering amplitudes become essential. In Fig. 2, we have shown all these interactions, including the gluon attachments to the incident quarks (a,c), and final state balancing quark (d) and the internal gluon propagator (b). Although these diagrams are much more complicated than that discussed in [16] for SIDIS and e^+e^- processes, we can still study their contributions, by classifying different momentum regions for the exchanged gluons. The dominant contribution to the fragmentation function comes from the kinematic region where the exchanged gluon is parallel to the final state hadron [20]. Otherwise, their contributions will be power suppressed in the limit of $P_{hT} \ll P_\perp$ [18, 20, 21]. For these collinear gluon interactions, we can use Ward identity and eikonal approximation to sum them together to form the gauge link in the definition of the fragmentation function [18, 20].

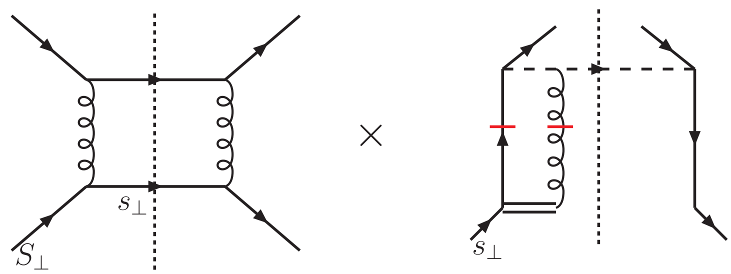

FIG. 3: *Factorize the contributions from Fig. 2 into the hard partonic cross section multiplied by the universal Collins fragmentation function. The short bars indicate the pole contribution to the Collins function.*

The contributing phases of the diagrams in Fig. 2 come from the cuts through the internal propagators in the partonic scattering amplitudes [16, 22]. In Fig. 2, we labelled these cut-poles by short bars in the diagrams. From our calculations, we find that all these poles come from a cut through the exchanged gluon and the fragmenting quark in each diagram, and all other contributions either vanish or cancel out each other [18]. For example, in Fig. 2(d), we show two additional cuts, which contribute however opposite to each other and cancel out completely. Therefore, by using the Ward identity at this particular order, the final results for all these diagrams will still sum up together into a factorized form as shown in Fig. 3, where the cross section is written as the hard partonic cross section for $q(S_\perp)q' \to q(s_\perp)q'$ subprocess multiplied by a Collins fragmentation function [18]. The exchanged gluon in Fig. 2 is now attaching to a gauge link from the fragmentation function definition [13]. The Collins fragmentation function can be calculated from this diagram, and it will not depend on the gauge link direction [19]. Clearly, this demonstrates the universality property [16, 17, 18], and the Collins function for our process will be the same as that in the SIDIS and e^+e^- annihilation processes. We emphasize this conclusion is model-independent. This observation is very different from that for the parton distributions, where the initial/final state interactions from the gluon exchange between the spectator and the active quark change the normal universality property for the so-called naive time-reversal-odd parton distributions, for which we will have opposite signs for the SIDIS and Drell-Yan processes [22, 23, 24].

With the universality property of the Collins fragmentation function, we can predict the azimuthal asymmetry of the hadron production inside a jet in the single transversely

polarized pp collisions from the knowledge of the Collins function in other processes [6, 8]. One interesting asymmetry is calculated from Eq. (4), by integrating over $|P_{hT}|$ while keeping the azimuthal dependence $\sin(\phi_h - \phi_s)$, and the cross section can be written as $d\sigma = d\sigma_{UU}\left(1 + A_N \sin(\phi_h - \phi_s)\right)$. The asymmetry A_N is defined as

$$A_N = \frac{\int dy_2 \sum_{qb} x' f_b(x') x \delta q_T(x) \delta\hat{q}^{(1/2)}(z_h) H^{\rm Collins}_{qb\to qb}}{\int dy_2 \sum_{abc} x' f_b(x') x f_a(x) D_c^h(z_h) H^{\rm UU}_{ab\to cd}} \ , \tag{6}$$

where $\delta\hat{q}^{(1/2)}(z_h)$ is the so-called 1/2-moment of the Collins function,

$$\delta\hat{q}^{(1/2)}(z_h) = \int d^2P_{hT} \frac{|P_{hT}|}{M_h} \delta\hat{q}(z_h, P_{hT}) \ . \tag{7}$$

The above functions for the pions have been fit to the HERMES data [6] in terms of unpolarized fragmentation functions: $\delta\hat{u}^{\pi^+(1/2)} = \delta\hat{d}^{\pi^-(1/2)} = C_f z(1-z) D_u^{\pi^+}$; $\delta\hat{u}^{\pi^-(1/2)} = \delta\hat{d}^{\pi^+(1/2)} = C_u z(1-z) D_u^{\pi^-}$, where $D_u^{\pi^+}$ and $D_u^{\pi^-}$ are also called favored and un-favored fragmentation functions for pions, respectively, and the coefficients are found as $C_f = -0.29$ and $C_u = 0.56$ [7], by using the quark transversity distributions parameterized in [4]. We noticed that the Collins asymmetries found in SIDIS and e^+e^- annihilation are also consistent with each other [9]. In Fig. 4, we plot the asymmetries of Eq. (6) for the charged and neutral pions at RHIC as functions of rapidity y_1 and transverse momentum $P_\perp$ of the jet. From these plots, we find that the asymmetries for the charged pions are sizable at forward rapidity region, whereas that for the neutral pion is very small due to the strong cancellation between the favored and unfavored Collins functions in the fit to the HERMES data [7]. It will be interested to compare with the predictions based on the quark transversity and Collins fragmentation functions obtained in [9].

4. Summary. In this paper, we have proposed to study the quark transversity distribution by measuring the azimuthal asymmetry of hadron production inside a jet in the single-transverse-spin dependent pp collisions at RHIC. We have argued the universality of the Collins function between this and other processes. By using the information on the Collins functions from HERMES experiment, we predicted the azimuthal asymmetries for charged and neutral pions in a jet at RHIC, and the SSAs for the charged pions are found sizable in forward region of the polarized proton beam. The experimental study of these asymmetries will be crucial to test the universality of the Collins fragmentation function, and provide us important information on the quark transversity distributions.

A number of extensions can be followed based on our study. One of the important issues is the QCD factorization. In our calculation, we assumed the factorization works,

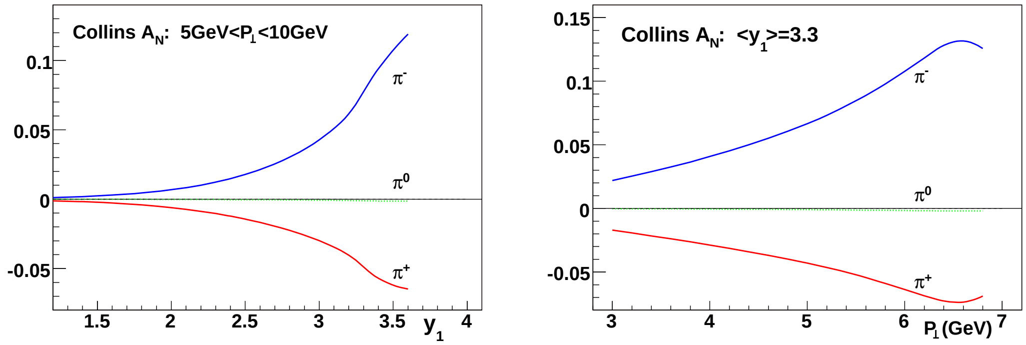

FIG. 4: *Collins SSAs calculated from Eq. (4) for pions in a jet in pp collision at* $\sqrt{s} = 200GeV$ *at RHIC: left panel as functions of the jet rapidity* y_1*; right panel as functions of the jet transverse momentum* $P_\perp$*.*

and demonstrated the universality of the Collins function in a model calculation. It will be crucial to show this property in a real QCD framework. Another important aspect associated with the Collins function is the connection with the quark-gluon correlation contribution in the fragmentation process [25, 26]. We reserve these further studies in a future publication, together with a detailed derivation of our results in this paper.

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